



Graphitic carbon nitride co-modified by zinc phthalocyanine and graphene quantum dots for the efficient photocatalytic degradation of refractory contaminants



Tiefeng Xu, Dongni Wang, Lulu Dong, Haibin Shen, Wangyang Lu*, Wenxing Chen*

National Engineering Lab for Textile Fiber Materials & Processing Technology (Zhejiang), Zhejiang Sci-Tech University, Hangzhou, 310018, China

ARTICLE INFO

Keywords:

Graphitic carbon nitride
Phthalocyanine
Graphene quantum dots
Electron transfer
Degradation pathway

ABSTRACT

Broad solar light absorption and rapid photogenerated electron-hole pair separation are two critical factors for the efficient enhancement of catalytic performance in a g-C₃N₄-based photocatalytic system. This study developed a facile method to construct a ternary graphitic carbon nitride/zinc tetracarboxyphthalocyanine/graphene quantum dots (g-C₃N₄/ZnTcPc/GQDs) composite photocatalyst. Graphene quantum dots (GQDs) were used to modify g-C₃N₄/ZnTcPc through hydrothermal method, where g-C₃N₄/ZnTcPc was fabricated by immobilizing zinc tetracarboxyphthalocyanine (ZnTcPc) onto g-C₃N₄ covalently via amido bonds. The photocatalyst was characterized by transmission electron microscopy, ultraviolet-visible diffuse reflectance spectrum, and X-ray photoelectron spectroscopy. The g-C₃N₄/ZnTcPc/0.1GQDs composites presented an increased photocatalytic activity by using Rhodamine B, sulfaquinoxaline sodium and carbamazepine as the model pollutants under solar light irradiation. ZnTcPc bonding on the g-C₃N₄ broadens its visible-light spectral response, and GQDs promotes the photogenerated electron-hole-pair separation efficiency because of its efficient electrons-transfer property. Experiments confirmed that superoxide radicals, photogenerated holes and singlet oxygen are the primary active species. The photocatalytic degradation pathway of Rhodamine B, sulfaquinoxaline sodium and carbamazepine was proposed on the basis of ultra-performance liquid chromatography and high-definition mass spectrometry.

1. Introduction

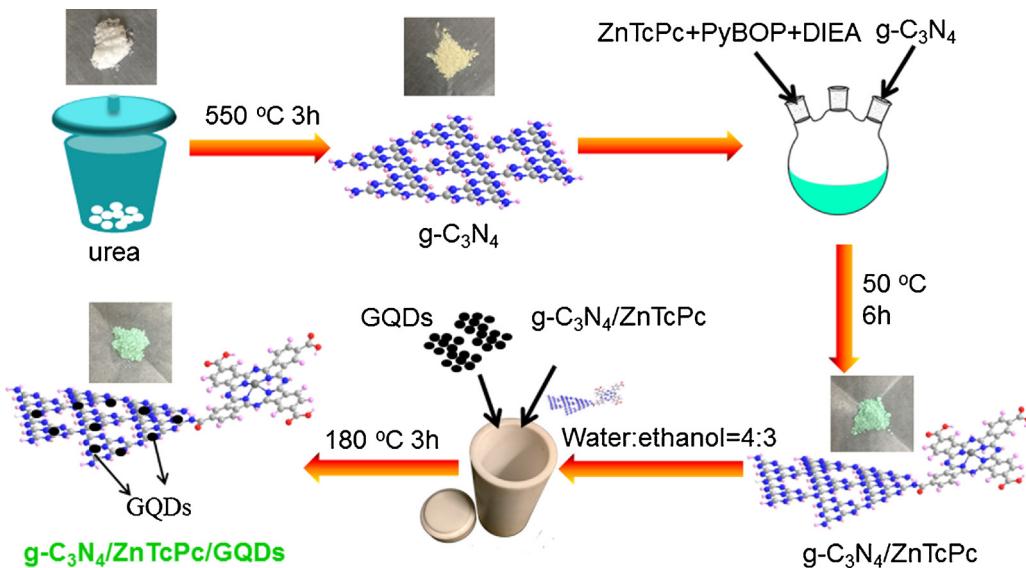
Abundant poisonous and refractory pollutants such as pharmaceuticals and personal care products [1], and some organic conjugate compounds in the environment are produced accompanied by rapid industrial development and population growth. These pollutants have become a severe global environmental problem [2,3]. An awareness of the presence of these hazardous pollutants in the environment, including in surface water, groundwater, and particularly in wastewater should initiate precautionary management action to reduce disastrous impacts on the environment [4–6]. Semiconductor photocatalysis can be considered an ideal and feasible strategy for environmental governance, particularly to remove poisonous and refractory organic compounds from wastewater [7–9].

Graphitic carbon nitride (g-C₃N₄) [10] as a metal-free organic-polymeric semiconductor with a visible-light response, has attracted widespread concern in photocatalytic hydrogen generation [11–13], CO₂ photocatalytic conversion [14–16] and organic contaminant degradation [17,18], because of its merits of environmental friendliness,

reliable stability and adjustable electronic properties. Meanwhile, g-C₃N₄ as two-dimensional material can provide enough reactive sites on the surface. Nevertheless, two primary characteristics restrict its photocatalytic activity, namely, a comparatively unsatisfactory utilization of solar light and the rapid recombination of photogenerated electron-holes pair. Various strategies have been exploited to overcome these issues, and improvements in g-C₃N₄ have resulted, including its coupling with other semiconductors [19–21], doping with non-metallic or metallic elements [22–25], fabrication of different morphologies [26–29] and sensitization with compounds [30–32]. Metal phthalocyanine (Mpc) is a well-known chromophore and it can be exploited as a dye for the sensitization of semiconductors that are absorbed internally in the visible region with the Soret band in the ultraviolet/blue spectral regions and the Q band centered at ~650–800 nm in the red/near infrared (NIR) spectral regions [33–35]. Mpc are favorable catalysts because of their accessibility and excellent photochemical and thermal stabilities [36]. In our previous study, the breakthrough of ZnPc as sensitizer was achieved in g-C₃N₄-based photocatalytic systems to eliminate poisonous organic pollutants [37]. The sensitization of

* Corresponding authors.

E-mail addresses: luwy@zstu.edu.cn (W. Lu), wxchen@zstu.edu.cn (W. Chen).



Scheme 1. Schematic for the synthesis process of $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/\text{GQDs}$.

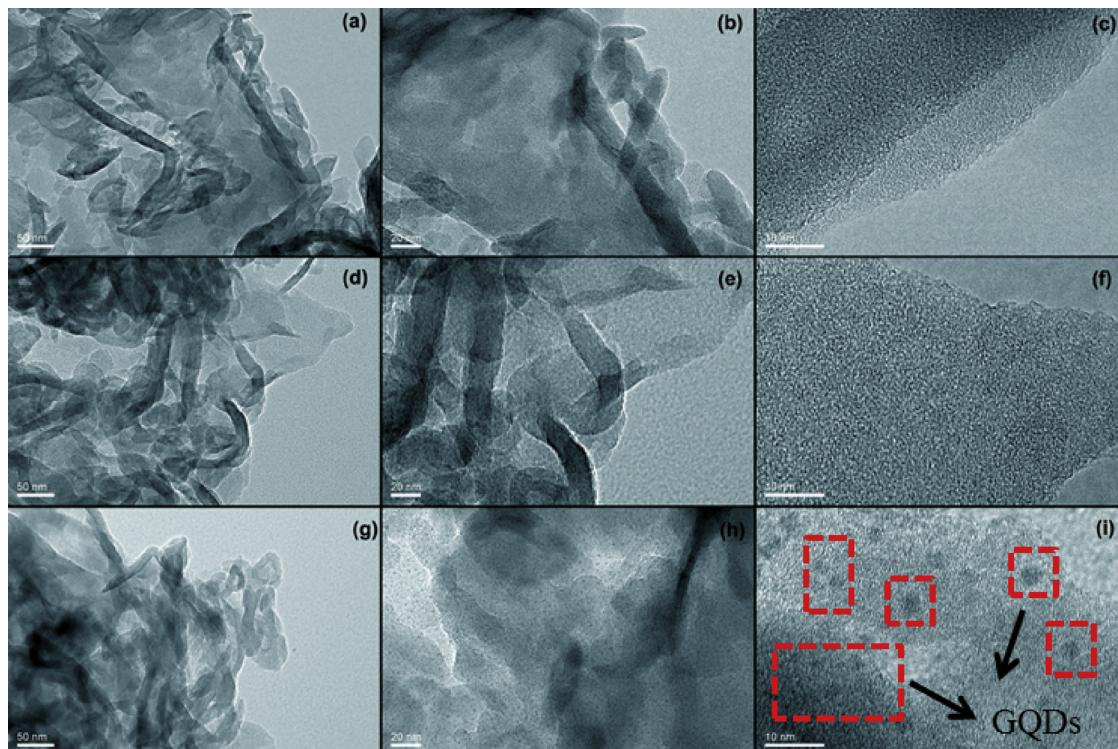


Fig. 1. TEM images of $\text{g-C}_3\text{N}_4$ (a,b,c), $\text{g-C}_3\text{N}_4/\text{ZnTcPc}$ (d,e,f) and, $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ (g,h,i).

ZnPc can widen the visible-light response range of $\text{g-C}_3\text{N}_4$ from 450 nm to more than 700 nm.

However, it is a biggest obstacle to achieve the extension of visible light response and the effective charge separation simultaneously in the binary photocatalytic system. The effective separation of photo-generated carriers must be implemented to increase the photocatalytic activity, where photogenerated electron-hole pair should be separated and transferred into the valence band (VB) and conduction band (CB) of opposite semiconductor. Carbon materials are appropriate candidates because of their superior optical and excellent electron-transfer properties, including carbon nanotube [38,39], carbon quantum dots [40,41], graphene [42], and graphene quantum dots [43,44]. Among them, graphene quantum dots (GQDs) with dimensions less than 10 nm

in diameter possess a unique character and have attracted attention to improve the photocatalytic performance of semiconductor materials. It is promising that $\text{g-C}_3\text{N}_4$ -based binary photocatalysts can be combined with highly conductive GQDs by electrostatic, π - π stacking and hydrogen-bonding interactions. Because of its nanoscale, it can be distributed evenly on the $\text{g-C}_3\text{N}_4$ surface without affecting the photocatalyst ability to absorb light.

Herein, we prepared a ternary $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/\text{GQDs}$ composite photocatalyst by dye sensitization and modification with carbon materials, and applied this catalyst to degrade Rhodamine B (RhB), sulfaquinoxaline sodium (SQXNa) and carbamazepine (CBZ) under solar light irradiation. The morphology structures, chemical components, and optical

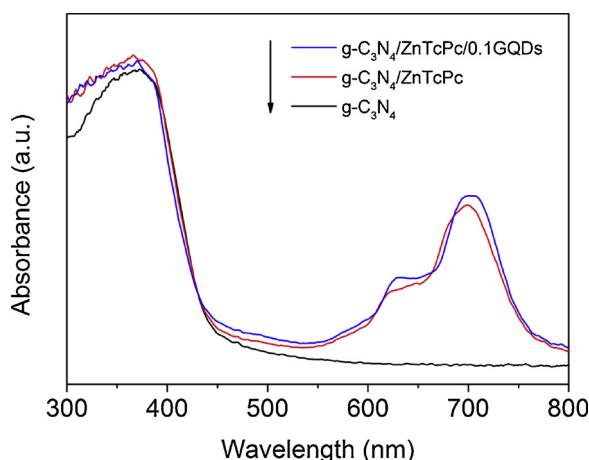


Fig. 2. UV-vis DRS absorption spectrum of $\text{g-C}_3\text{N}_4$, $\text{g-C}_3\text{N}_4/\text{ZnTcPc}$ and $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$.

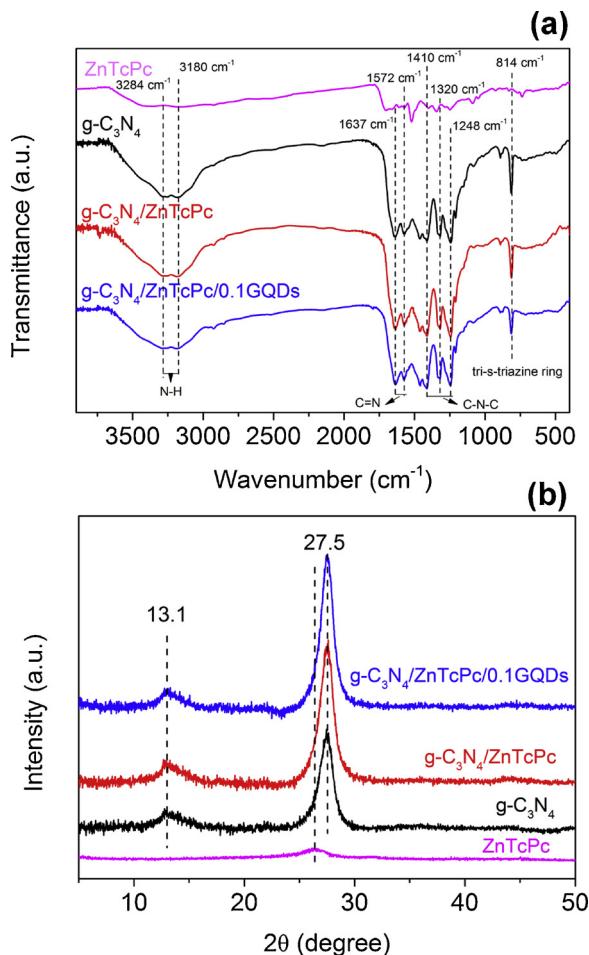


Fig. 3. FTIR (a) and XRD (b) spectra of ZnTcPc, $\text{g-C}_3\text{N}_4$, $\text{g-C}_3\text{N}_4/\text{ZnTcPc}$, $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$.

properties of the composite photocatalyst were investigated via a series of characterizations, and the effects of the amounts of GQDs, pH, and catalyst stability are discussed. An increased visible-light spectral response and effective charge separation are achieved simultaneously in the ternary photocatalytic system. Additionally, the existence of superoxide radicals ($\cdot\text{O}_2^-$), photogenerated holes (h^+) and singlet oxygen (${}^1\text{O}_2$) has been evidenced in the $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/\text{GQDs}$ catalytic system. A feasible photocatalytic mechanism of $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/\text{GQDs}$ has been

proposed. The photocatalytic degradation pathway for RhB, SQXNa and CBZ was proposed based on the detection of intermediates through ultra-performance liquid chromatography and high-definition mass spectrometry (UPLC/HDMS).

2. Experimental

2.1. Photocatalyst preparation

$\text{g-C}_3\text{N}_4$ and ZnTcPc were synthesized according to the literature with modifications [45–47]. $\text{g-C}_3\text{N}_4$ was prepared by a facile calcination strategy of urea. The urea in a covered crucible was heated at 550 °C for 3 h at 2.5 °C/min in a tube furnace. After being cooled to room temperature, the resulting faint yellow powder was collected for further use. The synthetic method and optimal ratio of $\text{g-C}_3\text{N}_4/\text{ZnTcPc}$ composite photocatalysts were consistent with previous literature methods [37].

$\text{g-C}_3\text{N}_4/\text{ZnTcPc}/\text{GQDs}$ composite photocatalysts were fabricated via a hydrothermal method. First, the as-prepared $\text{g-C}_3\text{N}_4/\text{ZnTcPc}$ (200 mg) and a certain amount of GQDs aqueous solution (0.12 mL, 0.16 mL, 0.20 mL, 0.24 mL, 0.28 mL, 1 mg/mL) were dispersed in a mixture solution of ethanol and water with ultrasonication for 1 h in a typical synthesis, where the volume ratio of water and alcohol was 4:3. The disperse solution was treated at 453 K for 3 h in a Teflon-lined stainless steel autoclave. The final product was collected by centrifugation, washed three times with ultrapure water and ethanol, and then dried by freeze drying at 223 K for 18 h. The obtained samples were termed $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.06\text{GQDs}$, $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.08\text{GQDs}$, $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$, $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.12\text{GQDs}$ and $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.14\text{GQDs}$ for the GQDs feeding amount of 0.12 mL, 0.16 mL, 0.20 mL, 0.24 mL, 0.28 mL, respectively. The preparation process of the $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/\text{GQDs}$ composite photocatalysts is depicted in Scheme 1.

2.2. Characterization

Transmission electron microscope (TEM) and high resolution transmission electron microscopy (HRTEM) graph (JEOL, JEM-2010) were obtained to study the morphology and microstructure images. Ultraviolet-visible diffuse reflection spectra (UV-vis DRS) were obtained from 300 to 800 nm with a Hitachi UH4150 spectrometer. Fourier-transform infrared spectroscopy (FTIR) spectra were recorded using a Thermo Nicolet 5700 analyzer to investigate the structure of as-prepared samples. The chemical environments of the as-prepared photocatalysts were analyzed by X-ray photoelectron spectroscopy (XPS) (Thermo Fisher Scientific) with a monochromatic Al-K α source operated at 1486.6 eV. The crystal structures of the photocatalysts were performed by X-ray diffraction (XRD) using a Bruker AXS D8-discover diffractometer operating with Cu-K α radiation in the range of 2 θ from 5° to 50°. The total organic carbon (TOC) content of the samples was analyzed by a liquiToc-2 analyzer (Elementar, Germany).

The photoelectrical properties were measured on a CHI660E electrochemical workstation (Chenhua Instrument) using 0.1 M Na_2SO_4 as an electrolyte solution including a three-electrode cell system with the prepared photocatalysts on carbon paper as the working electrode, an Ag/AgCl wire (saturated KCl solution) as reference electrode, and Pt wire as the counter electrode. The light source was a 100 W lamp (LOT-oriel GmbH & Co. KG). The working electrodes were prepared as follows: catalyst was dispersed into a mixed solution of ultrapure water, isopropanol and perfluorosulfonic acid polymer (Nafion), then the suspension was spread onto a 1 cm × 5 cm carbon paper substrate and dried at 60 °C. Electron paramagnetic resonance (EPR) technology (Bruker A-300) was used to confirm the possible active species under solar light irradiation. The settings for the EPR spectrometer were as follows: sweep width, 100 G; microwave frequency, 9.86 G; modulation frequency, 100 kHz; power, 20 mW.

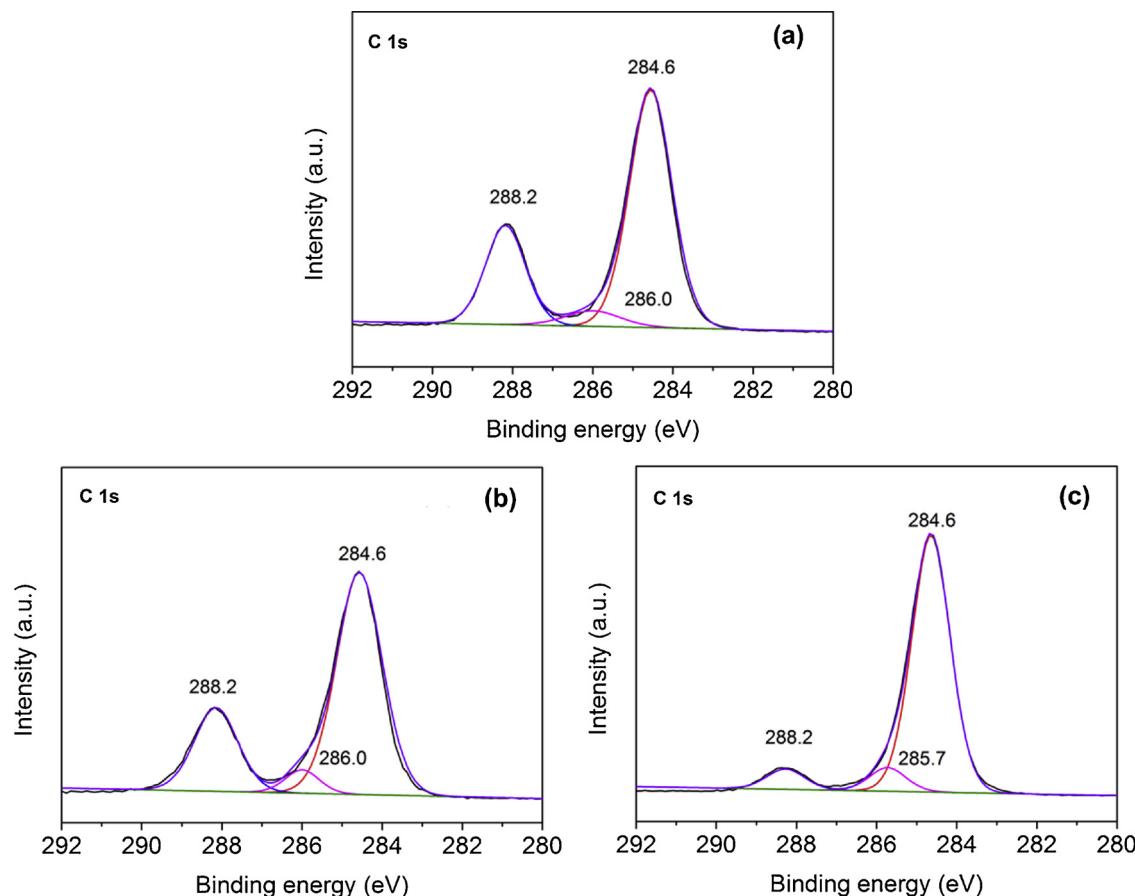


Fig. 4. Curve fit of the C 1s peak of (a) $\text{g-C}_3\text{N}_4$, (b) $\text{g-C}_3\text{N}_4/\text{ZnTcPc}$ and (c) $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$.

2.3. Photocatalytic experiments

Photocatalytic measurements of the as-prepared catalysts were conducted by using different organic pollutants as the target pollutants with a Q-Sun Xe-1 test chamber (USA), with RhB was an organic conjugate compound, and SQXNa and CBZ were the representative antibiotic and antiepileptic drugs respectively. The spectral power distribution of the Q-SUN Xe-1 is shown in Fig. S1. Substrate aqueous solution (20 mL, 2×10^{-5} mol/L) that contains 2 mg of photocatalyst (0.1 g/L) was transferred into the reactor. Prior to light irradiation, the mixture was treated by ultrasonication for 10 min in the dark to obtain a uniform suspension. At a certain time interval, the solution was removed continually from the reactor and filtered to remove the photocatalyst particles. The RhB concentration was determined by UV-vis spectrometry (Hitachi, U3900 H) at 554 nm, and the concentrations of CBZ and SQXNa were monitored by ultra-performance liquid chromatography with a PDA detector (UPLC, Waters). The reaction system pH was adjusted by H_2SO_4 or NaOH addition.

2.4. Analytical methods

The degradation intermediates and final products of RhB, SQXNa and CBZ over $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/\text{GQDs}$ were analyzed by UPLC/HDMS (Waters, Synapt G2-S) with an electrospray ionization (ESI) source. A HSS T3 column ($1.8 \mu\text{m}$, $2.1 \times 100 \text{ mm}$) was used to separate the relevant components at a flow rate of 0.4 mL/min . In positive mode, the mobile phase was composed of water (solvent A) and acetonitrile or methanol (RhB: methanol, SQXNa and CBZ: acetonitrile, solvent B). An eluent gradient schedule for the intermediates detection of RhB was used during the separation: from 0 to 1.0 min, 60% A; from 1.0 to 7.0 min, 60%-30% A (linear); from 7.0 to 8.0 min, 30% A; from 8.0 to

8.1 min, 30%-60% A (linear); and from 8.1 to 10.0 min, 60% A. The eluent gradient schedule for the intermediates detection of SQXNa and CBZ was as follows: from 0 to 0.3 min, 90% A; from 0.3 to 8 min, 90%-10% A (linear); from 8.0 to 9.0 min, 10% A; from 9.0 to 9.1 min, 10%-90% A (linear); and from 9.1 to 10.0 min, 90% A. In negative mode, the mobile phase was composed of water or acidified water (0.1% formic acid, solvent A) and methanol (solvent B). An eluent gradient schedule was used during the separation: from 0 to 0.2 min, 99% A; from 0.2 to 6 min, 99%-80% A (linear); from 6 to 8.5 min, 80%-40% A (linear); from 8.5 to 9.0 min, 40% A; from 9.0 to 9.1 min, 40%-99% A (linear); and from 9.1 to 10 min, 99% A. The source and desolvation temperature were set to 120°C and 500°C , respectively. Nitrogen was used as the cone gas (50.0 L/h) and desolvation gas (600.0 L/h). The scan range was set to m/z 50–1200.

3. Results and discussion

3.1. Characterization

The morphology and microstructure of as-prepared $\text{g-C}_3\text{N}_4$, $\text{g-C}_3\text{N}_4/\text{ZnTcPc}$ and $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/\text{GQDs}$ were exhibited by TEM in Fig. 1a–i. According to the TEM images (Fig. 1a–c.), $\text{g-C}_3\text{N}_4$ has a thin lamellar structure, which could lead to a larger specific surface area and more reactive sites. When ZnTcPc was immobilized onto $\text{g-C}_3\text{N}_4$ covalently via amido bonds, Fig. 1d–f shows that the lamellar structure of $\text{g-C}_3\text{N}_4$ has no apparent difference before and after the introduction of ZnTcPc. No ZnTcPc is visible in the TEM or HMTEM images (Fig. 1f), which indicated that ZnTcPc did not exist in crystals but exists as small molecules. Fig. 1h shows that the GQDs were well dispersed uniformly and the $\text{g-C}_3\text{N}_4$ was covered by numerous GQDs. In accordance with previous work, the relatively low contrast degree of the TEM image was

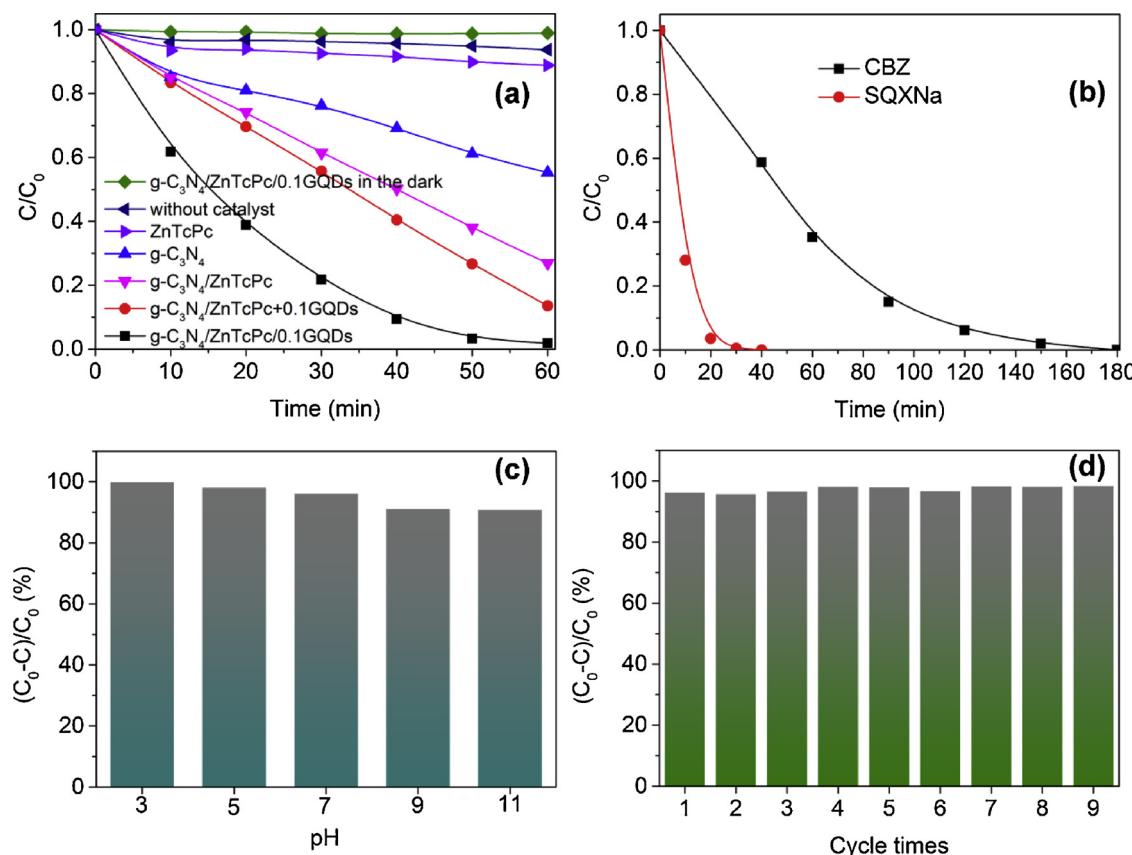


Fig. 5. (a) Photocatalytic degradation of RhB in the presence of g-C₃N₄, g-C₃N₄/ZnTcPc and g-C₃N₄/ZnTcPc/0.1GQDs under solar light irradiation, pH = 5.3; (b) Photocatalytic degradation of CBZ and SQXNa in the presence of g-C₃N₄/ZnTcPc/0.1GQDs under solar light irradiation, (c) The removal rate of RhB at different pH in the presence of g-C₃N₄/ZnTcPc/0.1GQDs under soalr light irradiation. (d) The cyclic catalytic oxidation of RhB under solar light irradiation after 60 min. [RhB] = 20 μM, [CBZ] = [SQXNa] = 25 μM, [g-C₃N₄] = [ZnTcPc] = [g-C₃N₄/ZnTcPc] = [g-C₃N₄/ZnTcPc + 0.1GQDs] = [g-C₃N₄/ZnTcPc/0.1GQDs] = 0.1 g/L.

assigned to the single-layered or few-layered structure of the GQDs [48]. Fig. 1*i* shows that the GQDs were well anchored on the g-C₃N₄ nanosheet surface and the average GQD size was ~2–6 nm.

The DRS spectra of as-prepared samples in Fig. 2 were used to study their optical properties, and they showed the effect of ZnTcPc and GQDs on the visible-light absorption range of g-C₃N₄. The pure g-C₃N₄ possessed an absorption edge at ~460 nm, which corresponded to its relatively large bandgap energy of 2.7 eV. g-C₃N₄/ZnTcPc revealed a better visible light absorption, where the maximum absorption wavelength was ~700 nm. The g-C₃N₄/ZnTcPc/GQDs photocatalyst also maintained superior visible-light-absorption properties. Therefore, we concluded that ZnTcPc broadened the visible-light response range of g-C₃N₄ and the strong electron-transfer interaction between g-C₃N₄/ZnTcPc and GQDs may induce a synergistic effect to enhance the photoactivity of g-C₃N₄/ZnTcPc.

Additionally, the structure of as-prepared catalysts was analyzed by FT-IR (Fig. 3a). In the FT-IR spectrum of ZnTcPc, the intensive band at ~1705 cm⁻¹ was indicative of the absorption by carbonyl stretching. The characteristic peaks at ~1087, 1250, 1345 and 1522 cm⁻¹ may be related to the skeleton stretching of ZnTcPc [49,50]. Pure g-C₃N₄ exhibited characteristic FT-IR absorption peaks similar to that in previous reports [51,52]. The characteristic peak at 814 cm⁻¹ corresponded to typical tri-s-triazine ring units. The absorption peaks for pure g-C₃N₄ in the region of 1200–1600 cm⁻¹ were ascribed to the classical stretching modes of C–N heterocycles. Peaks from 3000 and 3600 cm⁻¹ were caused by the existence of stretching modes of terminal NH₂ or NH groups that originated from the defect sites of the aromatic ring. The characteristic peaks of g-C₃N₄/ZnTcPc and g-C₃N₄/ZnTcPc/0.1GQDs were similar to those of g-C₃N₄. However, the characteristic peaks of ZnTcPc and GQDs could not be detected from the FTIR spectra of g-

C₃N₄/ZnTcPc and g-C₃N₄/ZnTcPc/0.1GQDs, because of their trace amount and the strong stretching vibration peaks of g-C₃N₄.

The phase and structure of ZnTcPc, g-C₃N₄, g-C₃N₄/ZnTcPc and g-C₃N₄/ZnTcPc/0.1GQDs were measured by XRD. As shown in Fig. 3b, two distinct diffraction peaks at 13.1° and 27.5° for g-C₃N₄ agreed well with the reported standard, which corresponded to the (100) and (002) planes of g-C₃N₄ (JCPDS 87-1526) [44]. It is assigned to the characteristic graphitic-like layered stacking of CN-based materials. The g-C₃N₄/ZnTcPc and g-C₃N₄/ZnTcPc/0.1GQDs composites showed no obvious characteristic peaks attributed to ZnTcPc and GQDs, which may occur due to the low loading content and low crystallinity of ZnTcPc and GQDs in the as-prepared g-C₃N₄/ZnTcPc/0.1GQDs composite. This is consistent with the observation from FT-IR. Meanwhile, the ZnTcPc and GQDs modification has no significant influence on the graphitic-like layered stacking structure of g-C₃N₄.

The surface chemical composition of the as-prepared catalysts, and the chemical interactions between g-C₃N₄/ZnTcPc and GQDs were explored by XPS analysis. Figs. 4 and S2 present the C 1 s and N 1 s XPS spectra of g-C₃N₄, g-C₃N₄/ZnTcPc and g-C₃N₄/ZnTcPc/0.1GQDs. As shown in Fig. 4a, the C 1 s spectra of pure g-C₃N₄ could be split into three species at 284.6, 286.0, and 288.2 eV, which were attributed to C–C, C–NH₂ and N–C=N, respectively [53]. The C–NH₂ peak of g-C₃N₄/ZnTcPc/0.1GQDs was shifted to 285.7 eV, and the C–C peak of g-C₃N₄/ZnTcPc/0.1GQDs was elevated in comparison with the N–C=N peak (Fig. 4c). This may be due to the addition of GQDs, which possess many C–COOH and C–C bonds, and showed the co-existence of GQDs and g-C₃N₄/ZnTcPc in the composites, which indicated a good agreement between the observed TEM results. Specifically, the N 1 s peaks of all prepared catalysts may be deconvoluted to four species peaks at 398.7, 399.9, 401.0 and 404.2 eV. The signal peak at 398.7 eV

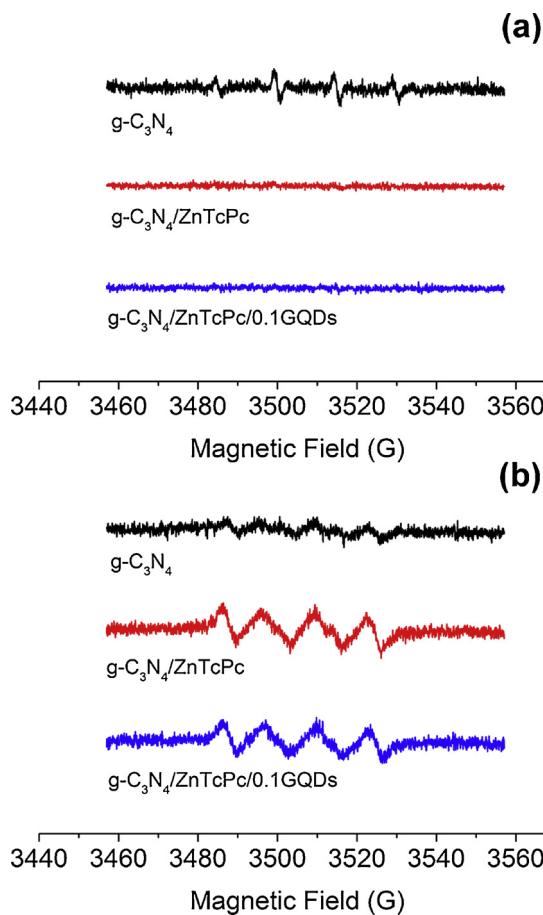


Fig. 6. DMPO spin-trapping EPR spectra in aqueous or methanol solutions in the presence of g-C₃N₄, g-C₃N₄/ZnTcPc and g-C₃N₄/ZnTcPc/0.1GQDs under solar light irradiation, (a) aqueous solution; (b) methanol solution. [DMPO] = 10 mM.

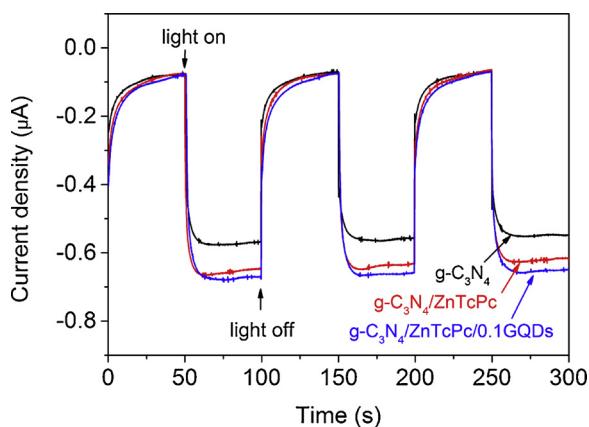


Fig. 7. Transient photocurrent density response of g-C₃N₄, g-C₃N₄/ZnTcPc and g-C₃N₄/ZnTcPc/0.1GQDs photocatalysts electrodes with light on-off cycles under solar light irradiation, [Na₂SO₄] = 0.1 M.

corresponds to sp²-hybridized nitrogen atoms in the triazine ring (C = N—C), which was consistent with the observation from the FT-IR analysis. The peak at 399.9 eV was attributed to the tertiary nitrogen bond to carbon atoms in N-(C)₃ or H-N-(C)₂, and the peak at 401.0 eV represented the amino function that carried hydrogen (C—N—H) of pure g-C₃N₄ in the aromatic cycles and the nitrogen of the amide group (—NH—CO—) formed for the bonding between the —NH₂ and —COOH [37]. The weaker peak at 404.4 eV may be assigned to π-excitation.

Taken together, these conclusions obtained in studies confirmed g-C₃N₄/ZnTcPc/GQDs has been synthesized successfully and it has the potential enhanced photocatalytic performance.

3.2. Photocatalytic activity

RhB, colorless SQXNa and CBZ were used to evaluate the photocatalytic activity of the as-prepared catalysts under solar light irradiation. Above all, Fig. S3 depicts the photocatalytic performance of g-C₃N₄/ZnTcPc/GQDs catalysts with different quantities of GQDs for RhB degradation. The photocatalytic efficiency of RhB increased gradually with larger quantities of GQDs, from 0.06 wt% to 0.1 wt%. However, a further GQDs loading increase resulted in a constant or further decreased degradation activity, which might be attributable to competition for light absorption between GQDs and g-C₃N₄, which reduced the formation of reactive species. Consequently, a suitable ratio between g-C₃N₄/ZnTcPc and GQDs is conducive to improve the photocatalytic activity and g-C₃N₄/ZnTcPc/0.1GQDs was chosen for further study. In Fig. 5a, the removal rate of RhB degradation almost had no change without any photocatalyst, which indicated that the direct photolysis of RhB could not be happened under solar light irradiation. ZnTcPc could barely degrade RhB, and g-C₃N₄ revealed an RhB removal rate of 44.7% within 60 min, whereas g-C₃N₄/ZnTcPc presented a removal efficiency of 73.1% for RhB degradation under the same conditions in Fig. 5a. Besides, g-C₃N₄/ZnTcPc/0.1GQDs exhibited no catalytic activity in the absence of a light source, which demonstrated that the catalysts had no adsorption toward the target substrate and the catalytic oxidation reaction must be driven by a light source. When g-C₃N₄/ZnTcPc/0.1GQDs was present, the removal rate of RhB exceeded 98.2%, which was approximately 2 times the photonic efficiency than that of pure g-C₃N₄. This result implied that g-C₃N₄/ZnTcPc/0.1GQDs possessed a higher catalytic oxidation capacity. In addition, the photocatalytic performance of g-C₃N₄/ZnTcPc/0.1GQDs was superior to a physical mixture of g-C₃N₄/ZnTcPc and the same amount of GQDs (g-C₃N₄/ZnTcPc + 0.1GQDs), which revealed a synergistic catalytic effect in the g-C₃N₄/ZnTcPc/0.1GQDs system. Besides, g-C₃N₄/ZnTcPc/0.1GQDs also exhibited a better photocatalytic activity of SQXNa within 40 min and CBZ within 180 min (Fig. 5b), which eliminated the sensitization effect on the degradation of RhB. The visible-light photocatalytic performances ($\lambda > 420$ nm) of g-C₃N₄/ZnTcPc/0.1GQDs towards the degradation of RhB, SQXNa, and CBZ are shown in Fig. S4. g-C₃N₄/ZnTcPc/0.1GQDs also possesses photocatalytic activity under visible light irradiation ($\lambda > 420$ nm). From the above results, we inferred that the synergistic effect between g-C₃N₄ with ZnTcPc and GQDs resulted in the enhanced activities of g-C₃N₄/ZnTcPc/GQDs, which will be confirmed in the following experiments. The degree of mineralization is important for evaluating the complete degradation of organic pollutants. Therefore, the TOC removal ratios of RhB, CBZ and SQXNa over g-C₃N₄/ZnTcPc/0.1GQDs are shown in Fig. S5. About 48% of RhB, and 63% SQXNa are mineralized to CO₂ and H₂O under solar light irradiation for 60 min and 40 min, respectively. And about 59% of CBZ are removed under solar light irradiation for 180 min. The mineralization process indicates that the g-C₃N₄/ZnTcPc/0.1GQDs photocatalyst has mineralization ability.

Because the reaction kinetics of catalytic oxidation is often affected by pH, the photocatalytic degradation of RhB in the g-C₃N₄/ZnTcPc/0.1GQDs system was explored at various pH values. The RhB removal rates remained relatively high over a wide pH range. In contrast, g-C₃N₄/ZnTcPc/0.1GQDs showed a better activity for the photocatalytic degradation of RhB in acidic and neutral conditions, than in alkaline condition as shown in Fig. 5c. Moreover, the catalyst stability is critical to assess its practical application, and thus, recycling experiments of g-C₃N₄/ZnTcPc/0.1GQDs were performed over nine reaction runs under uniform conditions. As shown in Fig. 5d, it could be observed that it displays no obvious deactivation after nine consecutive recycles for RhB degradation under solar light irradiation (each run lasted for 60 min),

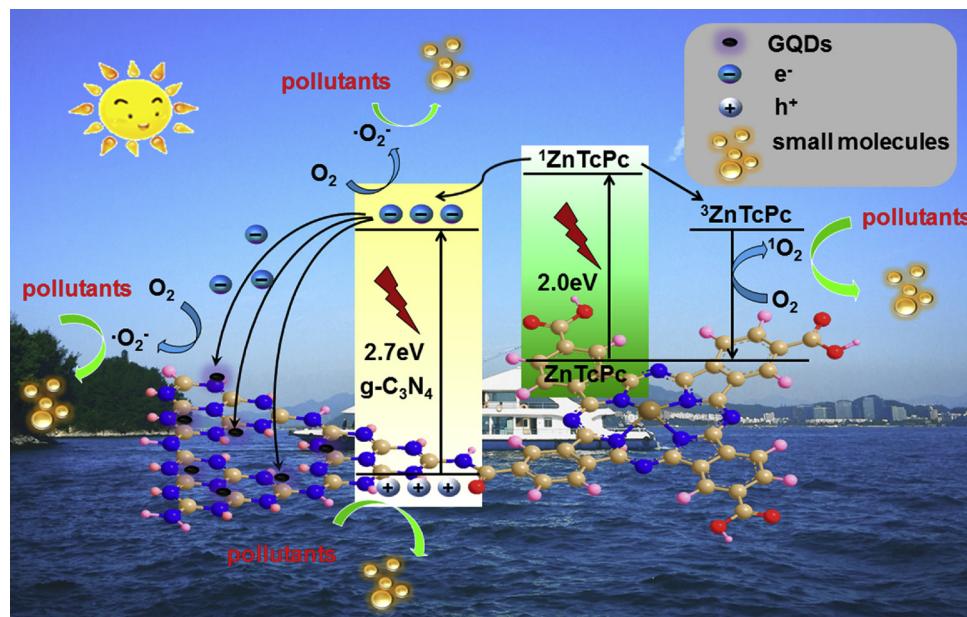


Fig. 8. Schematic diagram of possible reaction mechanism over $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ photocatalyst under solar light irradiation.

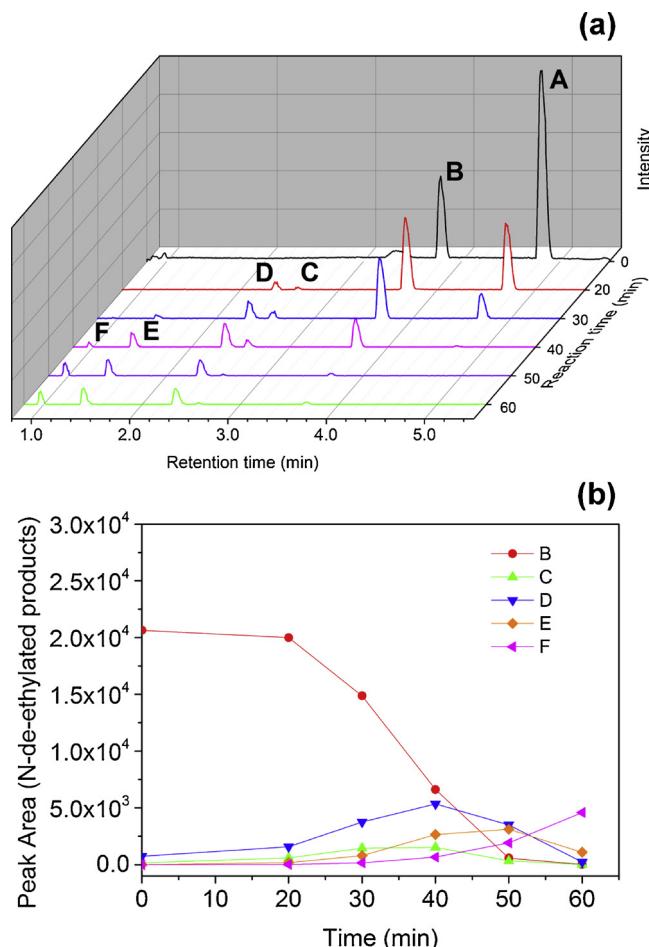


Fig. 9. Temporal UPLC spectra profiles (a) and temporal change in the distribution of the N-de-ethylated intermediates (b) during the photocatalytic degradation of RhB from UPLC Sy.

which disclosed that $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ possessed an excellent chemical stability and reliability for practical application. The XRD and FT-IR of the fresh and used $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ catalysts (before and after the ninth run cycle) were provided to highlight its stability (Fig. S6). It can be found that the structure and crystal phase had almost no apparent discrepancy between the fresh and used $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ composite. XPS was further employed to confirm the chemical composition of the used $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ after RhB degradation. The C1 s peaks in the XPS spectrum (Fig. S7) presented a similar result to the fresh $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$. The results pointed out that the catalyst is stable even after the ninth cycle of photocatalytic degradation.

3.3. Mechanism and pathway

3.3.1. Mechanism

EPR spin-trap technique tests were carried out in the photoreaction of $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQD}$ to achieve a better understanding of the possible reactive radicals. As a spin-trapping reagent, DMPO was exploited to capture $\cdot\text{OH}$ and $\cdot\text{O}_2^-$ [54,55]. As depicted in Fig. 6a, the water-dispersion liquid of the $\text{g-C}_3\text{N}_4/\text{ZnTcPc}$ and $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ composites was irradiated for 2 min and no $\cdot\text{OH}$ signals were detected, whereas $\cdot\text{OH}$ was generated in the $\text{g-C}_3\text{N}_4$ photocatalytic system. Hence, we concluded that $\cdot\text{OH}$ was not a species in the $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ photocatalytic reaction system. Four characteristic peaks of DMPO- $\cdot\text{O}_2^-$ were observed in the $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ system under solar light irradiation in Fig. 6b. $\cdot\text{O}_2^-$ was generated via a single-electron reduction process. $\cdot\text{O}_2^-$ produced during the $\text{g-C}_3\text{N}_4$ photocatalytic process was weaker than that of the $\text{g-C}_3\text{N}_4/\text{ZnTcPc}$ and $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ system, and its production could be ascribed to the electron transfer between $\text{g-C}_3\text{N}_4$ with ZnTcPc and GQDs. The participation of ${}^1\text{O}_2$ was also confirmed using 2,2,6,6-tetramethylpiperidine (TEMP) as the spin-trapping reagent under solar light irradiation in Fig. S8, with an intensity ratio of 1:1:1 that corresponded to the 2,2,6,6-tetramethylpiperidine N-oxyl (TEMPO) adduct. [56,57]. The EPR studies indicated that $\cdot\text{O}_2^-$ and ${}^1\text{O}_2$ were the dominant active species that were produced in this catalytic system. h^+ is usually regarded as the other dominant active species of $\text{g-C}_3\text{N}_4$. Thereby, free radicals trapping experiments were performed by using KI and BQ as h^+ and $\cdot\text{O}_2^-$ scavengers, respectively (Fig. S9). The photocatalytic degradation of RhB over $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ was inhibited

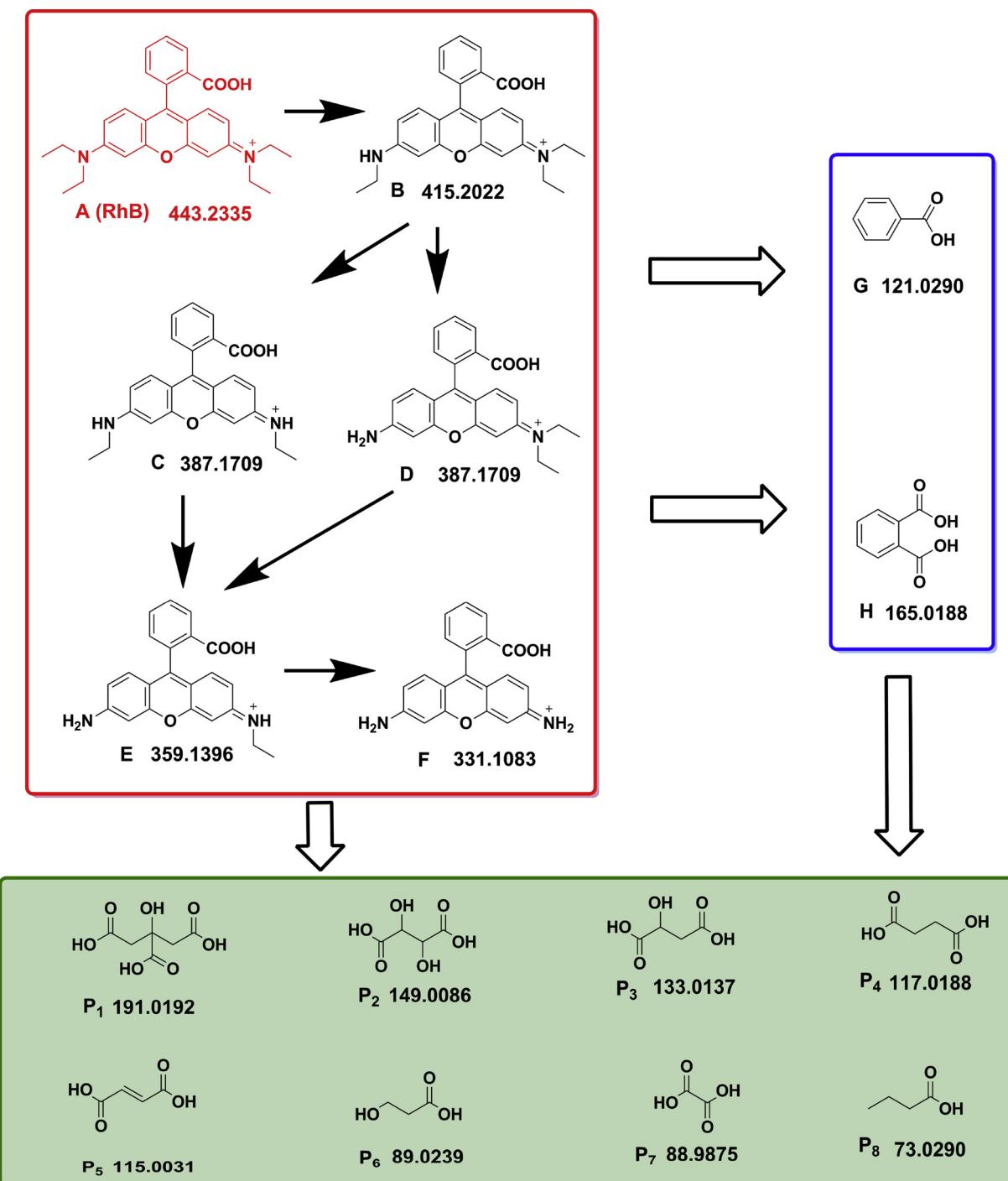


Fig. 10. Possible pathway for the photocatalytic degradation of RhB over $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ photocatalyst under solar light irradiation. [RhB] = 20 μM .

apparently after the addition of KI, suggesting that h^+ was another main active species in the photocatalytic process. Likewise, the degrading efficiency of RhB decreased in the presence of 1 mM BQ, which indicated a good agreement between the above EPR results.

The photocurrent-time measurement was deemed as an efficient way to prove the separation efficiency of photogenerated electron-hole pairs. As shown in Fig. 7, $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ exhibited the best photocurrent density response to light irradiation. This further demonstrated that the photogenerated electron-hole pairs of $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ could be separated efficiently compared with $\text{g-C}_3\text{N}_4$ and $\text{g-C}_3\text{N}_4/\text{ZnTcPc}$ though electronic transmission between $\text{g-C}_3\text{N}_4$ with ZnTcPc and GQDs.

From the results we have obtained, the possible photocatalytic mechanism for the target substrates degradation by $\text{g-C}_3\text{N}_4/\text{ZnTcPc}/0.1\text{GQDs}$ under solar light irradiation is proposed in Fig. 8. For ZnTcPc, the CB and VB were more negative than that of $\text{g-C}_3\text{N}_4$ [37]. Under solar light irradiation, $\text{g-C}_3\text{N}_4$ and ZnTcPc could be stimulated simultaneously. The excited electrons could be transferred from the lowest unoccupied molecular orbital (LUMO) of ZnTcPc to the conduction band of $\text{g-C}_3\text{N}_4$, while the photogenerated electrons on the CB of $\text{g-C}_3\text{N}_4$ can be further transferred to the GQDs surface rapidly to produce $\cdot\text{O}_2^-$, making photogenerated electrons-holes pair separation more effective and reducing the recombination probability. The formed $\cdot\text{O}_2^-$ and h^+ played an important role in the degradation of the above

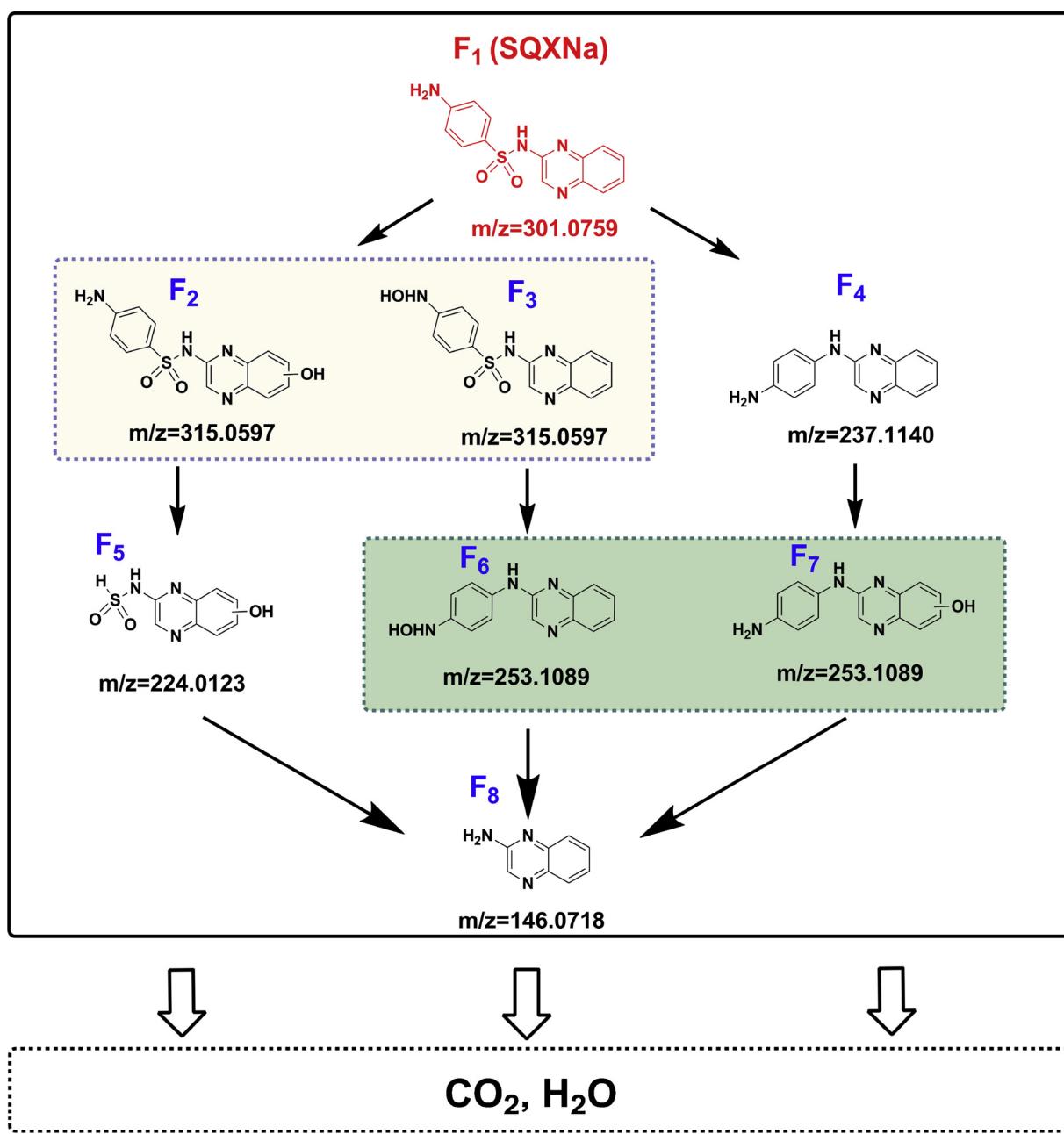


Fig. 11. Possible pathway for the photocatalytic degradation of SQXNa over g-C₃N₄/ZnTcPc/0.1GQDs photocatalyst under solar light irradiation. [SQXNa] = 25 μM.

pollutants. On the other hand, the generation of ¹O₂ may be attributed to the transformation between the ground state ZnTcPc and the excited state of ¹ZnTcPc and ³ZnTcPc [58]. In summary, [·]O₂⁻, h⁺, and ¹O₂ formed during the photocatalytic process lead to effective photocatalytic performance in the g-C₃N₄/ZnTcPc/0.1GQDs catalytic system.

3.3.2. Degradation pathway

Notwithstanding the target substrates can be degraded efficiently by g-C₃N₄/ZnTcPc/GQDs, transformation intermediates generated during the photocatalytic degradation may be underlying environmental pollutants. Consequently, the degradation intermediates of RhB, SQXNa and CBZ at different reaction times and the final products were analyzed using UPLC/HDMS. The UPLC chromatograms of RhB at different reaction times (0, 20, 30, 40, 50, and 60 min) are displayed in Fig. 9a. According to the UPLC chromatograms, peak A (*t*_R 4.70 min) was the maternal RhB, and peak B (*t*_R 3.66 min), C (*t*_R 2.60 min), D (*t*_R 2.33 min), E (*t*_R 1.39 min) and F (*t*_R 0.97 min) were N-de-ethylated

intermediates derived from the initial RhB [59,60]. The N-de-ethylated intermediate structures were detected by HDMS identification and these details are presented in Table S1. As can be seen, the intensity of peak A (RhB) decreased rapidly after reaction for 20 min (Fig. 9a), while the intensity of N-de-ethylated intermediates (B–E) increased initially and then decreased (Fig. 9b). The peak of F increased during the first 60 min and it was degraded after solar light irradiation. All N-de-ethylated intermediates underwent ring-opening mineralization, and eventually produced some biodegradable small molecular acids (Table S2). The UPLC/HDMS results allowed us to propose the possible degradation pathway of RhB (see Fig. 10). The N-ethyl group on the maternal RhB molecule was readily attacked by the active radicals [61], making for the formation of N-de-ethylated intermediates. The opening-ring and mineralization process took place subsequently, and benzoic acid, phthalic acid (G, H), and eight biodegradable small molecular acids (P₁–P₈) were produced by the cleavage of RhB and the N-de-ethylated intermediates with the extension of time.

Furthermore, we also propose the probable degradation pathway of SQXNa and CBZ over g-C₃N₄/ZnTcPc/GQDs under solar irradiation according to the UPLC/HDMS results (Figs. 11 and S10). The retention time of SQXNa was 4.15 min in the positive mode and the [SQ-Na + H]⁺ ion at *m/z* 301.0757 was yielded. Seven intermediates (F₂–F₈) are monitored in positive and negative ion modes. The corresponding parameters of these intermediates are listed in Tables S3. Firstly, the initial photodegradation products of SQXNa may undergo hydroxylation of the quinoxalin moiety to produce intermediates F₂ at *m/z* = 315.0597 [62], afterwards, intermediate F₅ was produced via the loss of the aniline group. Intermediate F₃ that has the same mass charge ratio as F₂ may be assumed to result from the ammonia molecule that was attacked by ·OH, and which lead to the formation of 4-(hydroxyamino)-N-(quinoxalin-2-yl)benzenesulfonamide [63]. Another degradation pathway was that SO₂ can be extruded easily from sulfonamides during the photocatalytic process, resulting in the F₄ ion (*m/z* = 237.1140) with the molecular formula of C₁₄H₁₂N₄ [64,65]. Subsequently, it was speculated that intermediate F₇ (*m/z* = 180.0815) was oxidized further to the compound at *m/z* = 253.1089 through ·OH attack. The F₆ ion at *m/z* = 253.1089 could be generated through SO₂ extrusion from the F₃ ion. The intermediate F₈ was formed by further oxidation of intermediate F₅–F₇. Finally, UPLC/HDMS was used to monitor the final products for the determination of SQXNa, but small molecular acids were not detected. We deduced that the mineralization of all intermediates into CO₂ and H₂O would occur, which was consistent with the results of TOC. The major degradation intermediates of CBZ detected by UPLC-Synapt G2-S HDMS were list in Table S4. Fig. S10 shows a possible degradation pathway of CBZ. Because the CBZ molecule's 10,11-double bond can be attacked by the reactive species easily [66,67], C₁ and C₂ were observed at *m/z* = 253.0977 ([M + H]⁺) as the initial photodegradation products. On the other hand, the cleavage of the C10-C11 bond of CBZ can also lead to the formation of intermediate C₄ [68]. Further oxidation of compound C₁ produced the relatively intermediate C₃ and C₅. Compound C₂ (*m/z* = 253.0977) can be also formed through the ring-contraction reaction of C₁, which could be further oxidized into compound C₈. The intermediates C₆ and C₇ at *m/z* of 236.0712 and 210.0919 indicate the loss of ammonia (-NH₃) and cyanic acid (-HOCH₃), respectively. Additionally, the formation of the compound C₉ is attributable to the hydrogen rearrangement reaction with the loss of the -CONH₂ group of compound C₂, that may subsequently undergo a second oxidation to yield acridine (compound C₁₀ at *m/z* of 180.0813) [69]. According to the results of TOC, these intermediates can eventually be mineralized into CO₂ and H₂O.

4. Conclusion

In summary, a ternary g-C₃N₄/ZnTcPc/GQDs composite photocatalyst was prepared successfully from g-C₃N₄ co-modified by ZnTcPc and GQDs through chemical bonding and hydrothermal methods. The ternary g-C₃N₄/ZnTcPc/GQDs composite exhibited efficient photocatalytic activity towards RhB, SQXNa and CBZ degradation under solar light irradiation. The introduction of ZnTcPc bonding on the g-C₃N₄ broadened the visible-light response range, and the GQDs dispersed uniformly on g-C₃N₄ surface, which facilitated efficient electrons transfer. Additionally, this system showed excellent photocatalytic performance over a wide pH range, and the presence of ¹O₂, ¹O₂⁻ and h⁺ were the main active species in the photodegradation of pollutants. Based on the UPLC/HDMS results, the photocatalytic degradation pathway for RhB, SQXNa and CBZ was proposed. Consequently, this study provides a novel strategy for the design of a highly efficacious composite photocatalyst to achieve the extension of the visible-light response and the effective charge-separation efficiency simultaneously in environmental remediation.

Conflict of interest

The authors declare no competing financial interest.

Author contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 51133006 and 51103133), Zhejiang Provincial Natural Science Foundation of China (No. LY14E030013).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.apcatb.2018.11.049>.

References

- [1] W.-L. Li, Z.-F. Zhang, W.-L. Ma, L.-Y. Liu, W.-W. Song, Y.-F. Li, Sci. Total Environ. 640–641 (2018) 1139–1147.
- [2] A.-K. Ghattas, F. Fischer, A. Wick, T.A. Ternes, Water Res. 116 (2017) 268–295.
- [3] E. Archer, B. Petrie, B. Kasprzyk-Hordern, G.M. Wolfaardt, Chemosphere 174 (2017) 437–446.
- [4] F. Bonvin, J. Omlin, R. Rutler, W.B. Schweizer, P.J. Alaimo, T.J. Strathmann, K. McNeill, T. Kohn, Environ. Sci. Technol. 47 (2013) 6746–6755.
- [5] A. Mirzaei, Z. Chen, F. Haghigat, L. Yerushalmi, Chemosphere 174 (2017) 665–688.
- [6] B.N. Bhadra, I. Ahmed, S. Kim, S.H. Jhung, Chem. Eng. J. 314 (2017) 50–58.
- [7] C.A. D'Amato, R. Giovannetti, M. Zannotti, E. Rommozz, S. Ferraro, C. Seghetti, M. Minicucci, R. Gunnella, A. Di Cicco, Appl. Surf. Sci. 441 (2018) 575–587.
- [8] A. Mallick, S. Roy, Nanoscale 10 (2018) 12713–12722.
- [9] F. Guo, W. Shi, H. Wang, M. Han, W. Guan, H. Huang, Y. Liu, Z. Kang, J. Hazard. Mater. 349 (2018) 111–118.
- [10] W.J. Ong, L.L. Tan, Y.H. Ng, S.T. Yong, S.P. Chai, Chem. Rev. 116 (2016) 7159–7329.
- [11] X. Wang, K. Maeda, A. Thomas, K. Takanabe, G. Xin, J.M. Carlsson, K. Domen, M. Antonietti, Nat. Mater. 8 (2009) 76–80.
- [12] S. Yang, Y. Gong, J. Zhang, L. Zhan, L. Ma, Z. Fang, R. Vajtai, X. Wang, P.M. Ajayan, Adv. Mater. 25 (2013) 2452–2456.
- [13] M. Zhu, S. Kim, L. Mao, M. Fujitsuka, J. Zhang, X. Wang, T. Majima, J. Am. Chem. Soc. 139 (2017) 13234–13242.
- [14] Y. He, L. Zhang, B. Teng, M. Fan, Environ. Sci. Technol. 49 (2015) 649–656.
- [15] W.J. Ong, L.L. Tan, S.P. Chai, S.T. Yong, Chem. Commun. 51 (2015) 858–861.
- [16] H. Shi, G. Chen, C. Zhang, Z. Zou, ACS Catal. 4 (2014) 3637–3643.
- [17] Y. Gong, X. Zhao, H. Zhang, B. Yang, K. Xiao, T. Guo, J. Zhang, H. Shao, Y. Wang, G. Yu, Appl. Catal. B Environ. 233 (2018) 35–45.
- [18] F. Chen, Q. Yang, Y. Wang, F. Yao, Y. Ma, X. Huang, X. Li, D. Wang, G. Zeng, H. Yu, Chem. Eng. J. 348 (2018) 157–170.
- [19] X. Wang, F. Wang, C. Bo, K. Cheng, J. Wang, J. Zhang, H. Song, Appl. Surf. Sci. 453 (2018) 320–329.
- [20] Y. Wang, W. Yang, X. Chen, J. Wang, Y. Zhu, Appl. Catal. B Environ. 220 (2018) 337–347.
- [21] H. Shao, X. Zhao, Y. Wang, R. Mao, Y. Wang, M. Qiao, S. Zhao, Y. Zhu, Appl. Catal. B Environ. 218 (2017) 810–818.
- [22] M.A. Mohamed, M.F.M. Zain, L. Jeffery Minggu, M.B. Kassim, N.A. Saidina Amin, W.N.W. Salleh, M.N.I. Salehmin, M.F. Md Nasir, Z.A. Mohd Hir, Appl. Catal. B Environ. 236 (2018) 265–279.
- [23] M. Jourshabani, Z. Sharifiatinia, A. Badiee, Appl. Surf. Sci. 427 (2018) 375–387.
- [24] O. Fontelles-Carceller, M.J. Munoz-Batista, M. Fernandez-Garcia, A. Kubacka, ACS Appl. Mater. Interfaces 8 (2016) 2617–2627.
- [25] C.H. Choi, L. Lin, S. Gim, S. Lee, H. Kim, X. Wang, W. Choi, ACS Catal. 8 (2018) 4241–4256.
- [26] X.-H. Li, J. Zhang, X. Chen, A. Fischer, A. Thomas, M. Antonietti, X. Wang, Chem. Mater. 23 (2011) 4344–4348.
- [27] Q. Han, B. Wang, Y. Zhao, C. Hu, L. Qu, Angew. Chem. Int. Ed. 54 (2015) 11433–11437.
- [28] J. Xu, Z. Wang, Y. Zhu, ACS Appl. Mater. Interfaces 9 (2017) 27727–27735.
- [29] Y. Chen, X. Wang, J. Phys. Chem. C 122 (2018) 3786–3793.
- [30] J. Wang, Y. Zheng, T. Peng, J. Zhang, R. Li, ACS Sustain. Chem. Eng. 5 (2017) 7549–7556.
- [31] J. Qin, J. Huo, P. Zhang, J. Zeng, T. Wang, H. Zeng, Nanoscale 8 (2016) 2249–2259.
- [32] J. Xu, Y. Li, S. Peng, G. Lu, S. Li, Phys. Chem. Chem. Phys. 15 (2013) 7657–7665.
- [33] H. Imahori, T. Umezawa, S. Ito, Accounts Chem. Res. 42 (2009) 1809–1818.
- [34] P. Brogdon, H. Cheema, J.H. Delcamp, ChemSusChem 11 (2018) 86–103.
- [35] D.O. Oluwole, F.A. Sari, E. Prinsloo, E. Dube, A. Yuzer, T. Nyokong, M. Ince,

Spectrochim. Acta A 203 (2018) 236–243.

[36] A.B. Sorokin, Chem. Rev. 113 (2013) 8152–8191.

[37] W. Lu, T. Xu, Y. Wang, H. Hu, N. Li, X. Jiang, W. Chen, Appl. Catal. B Environ. 180 (2016) 20–28.

[38] L. Ge, C. Han, Appl. Catal. B Environ. 117–118 (2012) 268–274.

[39] K.C. Christoforidis, Z. Syrgiannis, V. La Parola, T. Montini, C. Petit, E. Stathatos, R. Godin, J.R. Durrant, M. Prato, P. Fornasiero, Nano Energy 50 (2018) 468–478.

[40] J. Liu, Y. Liu, N. Liu, Y. Han, X. Zhang, H. Huang, Y. Lifshitz, S.-T. Lee, J. Zhong, Z. Kang, Science 347 (2015) 970.

[41] W.-J. Ong, L.K. Putri, Y.-C. Tan, L.-L. Tan, N. Li, Y.H. Ng, X. Wen, S.-P. Chai, Nano Res. 10 (2017) 1673–1696.

[42] X. Miao, X. Shen, J. Wu, Z. Ji, J. Wang, L. Kong, M. Liu, C. Song, Appl. Catal. A Gen. 539 (2017) 104–113.

[43] J. Liu, H. Xu, Y. Xu, Y. Song, J. Lian, Y. Zhao, L. Wang, L. Huang, H. Ji, H. Li, Appl. Catal. B Environ. 207 (2017) 429–437.

[44] M. Yan, Y. Hua, F. Zhu, L. Sun, W. Gu, W. Shi, Appl. Catal. B Environ. 206 (2017) 531–537.

[45] J. Liu, T. Zhang, Z. Wang, G. Dawson, W. Chen, J. Mater. Chem. 21 (2011) 14398.

[46] F. Dong, L. Wu, Y. Sun, M. Fu, Z. Wu, S.C. Lee, J. Mater. Chem. 21 (2011) 15171.

[47] J. Chen, N. Chen, J. Huang, J. Wang, M. Huang, Inorg. Chem. Commun. 9 (2006) 313–315.

[48] T.F. Yeh, C.Y. Teng, S.J. Chen, H. Teng, Adv. Mater. 26 (2014) 3297–3303.

[49] J. Hu, H. Liu, L. Wang, N. Li, T. Xu, W. Lu, Z. Zhu, W. Chen, Carbon 100 (2016) 408–416.

[50] J. Zhang, S. Sun, Y. Bian, W. Li, R. Liu, D. Zhao, Fuel 220 (2018) 513–520.

[51] H. Yan, H. Yang, J. Alloys. Compd. 509 (2011) L26–L29.

[52] H. Ji, F. Chang, X. Hu, W. Qin, J. Shen, Chem. Eng. J. 218 (2013) 183–190.

[53] J. Song, X. Wang, J. Ma, X. Wang, J. Wang, S. Xia, J. Zhao, Chem. Eng. J. 348 (2018) 380–388.

[54] F. Wu, H. Huang, T. Xu, W. Lu, N. Li, W. Chen, Appl. Catal. B Environ. 218 (2017) 230–239.

[55] H. Wang, D. Yong, S. Chen, S. Jiang, X. Zhang, W. Shao, Q. Zhang, W. Yan, B. Pan, Y. Xie, J. Am. Chem. Soc. 140 (2018) 1760–1766.

[56] S. Xu, P. Zhou, Z. Zhang, C. Yang, B. Zhang, K. Deng, S. Bottle, H. Zhu, J. Am. Chem. Soc. 139 (2017) 14775–14782.

[57] H. Wang, S. Jiang, S. Chen, D. Li, X. Zhang, W. Shao, X. Sun, J. Xie, Z. Zhao, Q. Zhang, Y. Tian, Y. Xie, Adv. Mater. 28 (2016) 6940–6945.

[58] M. Gao, N. Li, W. Lu, W. Chen, Appl. Catal. B Environ. 147 (2014) 805–812.

[59] X. Li, T. Wan, J. Qiu, H. Wei, F. Qin, Y. Wang, Y. Liao, Z. Huang, X. Tan, Appl. Catal. B Environ. 217 (2017) 591–602.

[60] B. Li, C. Lai, G. Zeng, L. Qin, H. Yi, D. Huang, C. Zhou, X. Liu, M. Cheng, P. Xu, C. Zhang, F. Huang, S. Liu, ACS Appl. Mater. Interfaces 10 (2018) 18824–18836.

[61] T. Xu, D. Ni, X. Chen, F. Wu, P. Ge, W. Lu, H. Hu, Z. Zhu, W. Chen, J. Hazard. Mater. 317 (2016) 17–26.

[62] Z. Zhu, W. Lu, N. Li, T. Xu, W. Chen, Chem. Eng. J. 321 (2017) 58–66.

[63] Q.-N. Liao, F. Ji, J.-C. Li, X. Zhan, Z.-H. Hu, Chem. Eng. J. 284 (2016) 494–502.

[64] A.L. Boreen, W.A. Arnold, K. McNeill, Environ. Sci. Technol. 39 (2005) 3630–3638.

[65] D. Qin, W. Lu, X. Wang, N. Li, X. Chen, Z. Zhu, W. Chen, ACS Appl. Mater. Interfaces 8 (2016) 25962–25970.

[66] Y. Pan, S. Cheng, X. Yang, J. Ren, J. Fang, C. Shang, W. Song, L. Lian, X. Zhang, Water Res. 116 (2017) 254–265.

[67] B. Yang, R.S. Kookana, M. Williams, J. Du, H. Doan, A. Kumar, Water Res. 100 (2016) 413–420.

[68] J. Xu, L. Li, C. Guo, Y. Zhang, W. Meng, Appl. Catal. B Environ. 130–131 (2013) 285–292.

[69] C. Martínez, M.L. Canle, M.I. Fernández, J.A. Santaballa, J. Faria, Appl. Catal. B Environ. 102 (2011) 563–571.